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UK CL (Edition J) G1G GER GEV
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(54) **A demodulator circuit for an interferometer type of hydrophone**

(57) The optical signal in a fiber optic interferometer (20) is phase modulated to provide a carrier signal for phase changes caused by changes in a physical parameter such as sound, being sensed. The signal is then demodulated to measure changes in the parameter. A crystal oscillator (52) frequency reference and passive filtering cause the circuit to have low phase noise. Digital phase shifters (96, 98) provide mixer references that have low phase noise and stable gain. The signal processing techniques used are applicable to sensor arrays using a single carrier excitation source, time demultiplexing of individual carrier signals and demodulation of each sensor carrier signal. This demodulator circuit is also applicable to frequency-multiplexed approaches, which utilize direct frequency modulation of the source slightly unbalanced interferometers, and electronic frequency-division multiplexing. The passive homodyne technique allows large linear dynamic range of about 100 dB so that both small and large amplitude signals commonly encountered in acoustic sensing applications may be observed with excellent fidelity.

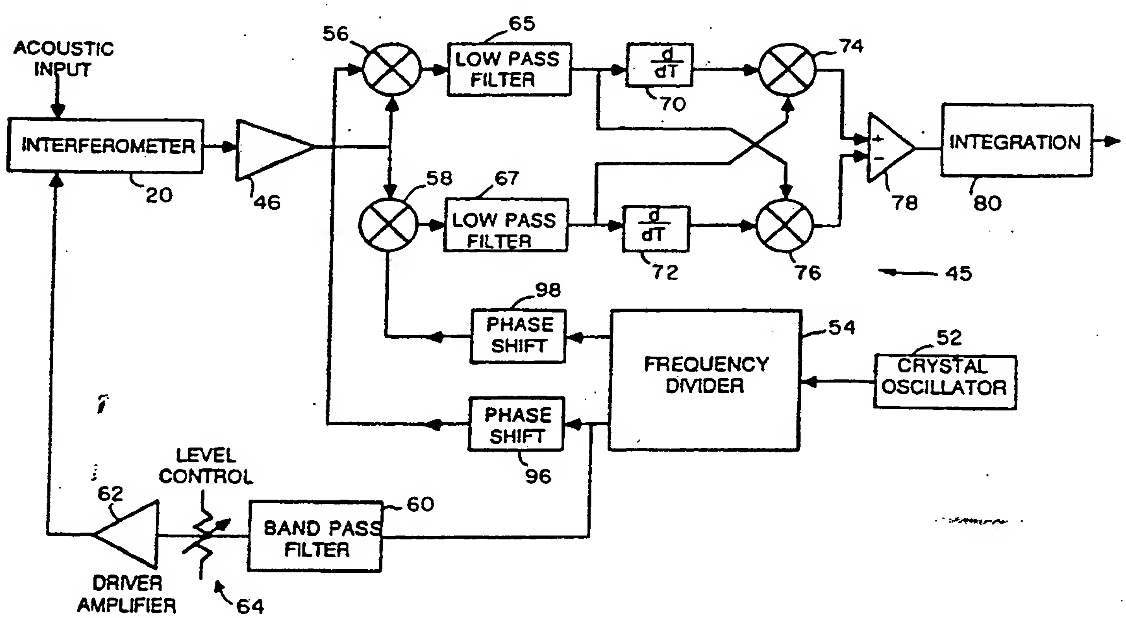


FIG.6

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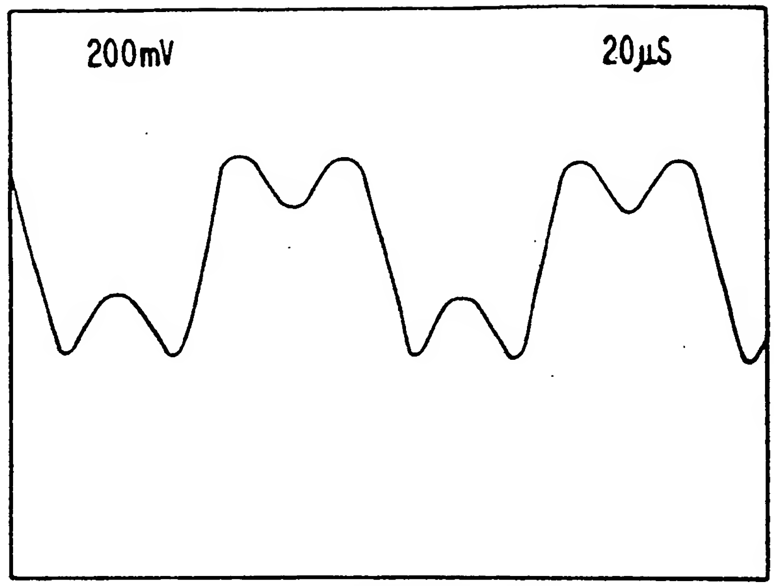



(a) OSCILLOSCOPE TRACE

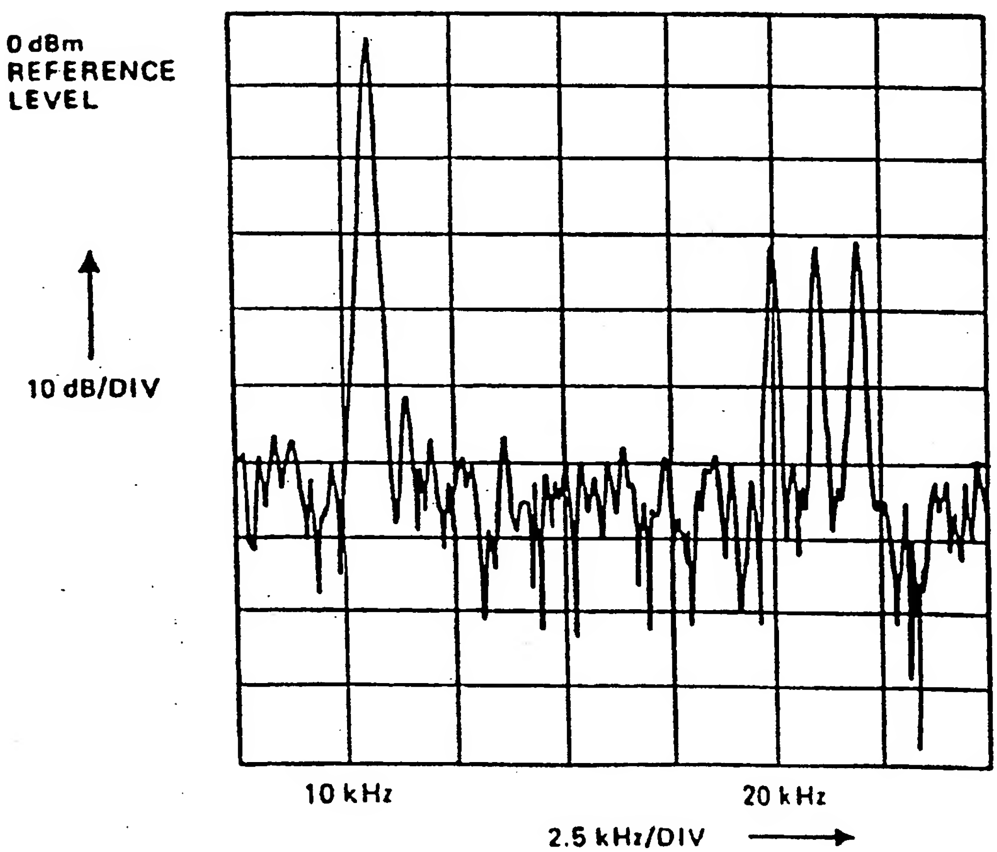
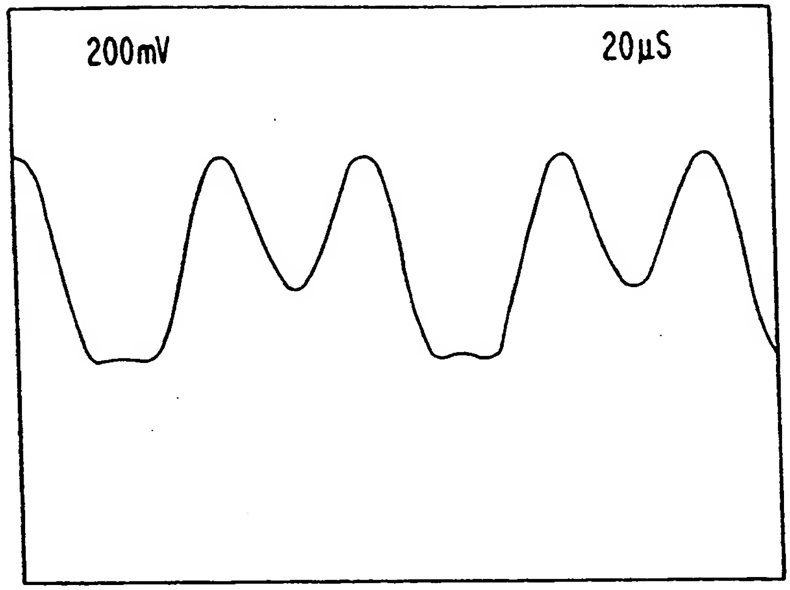



FIG.2 (b) SIGNAL SPECTRUM




(a) OSCILLOSCOPE TRACE

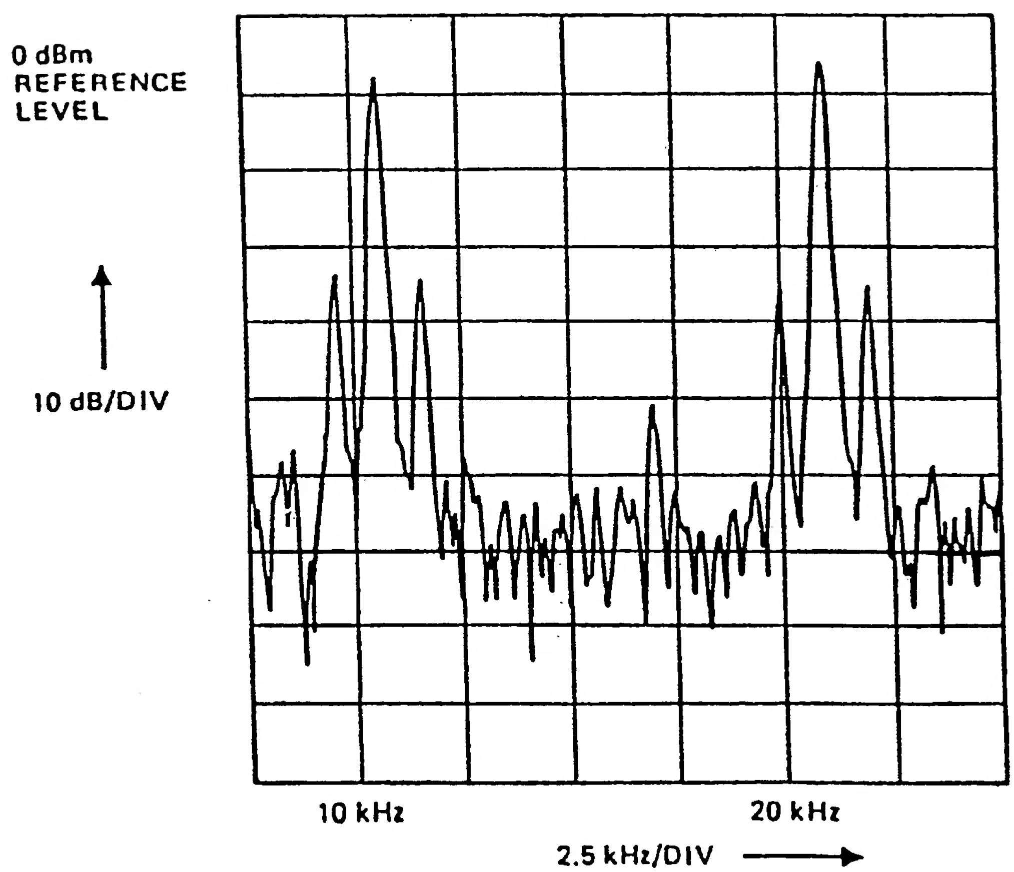



FIG. 4 (b) SIGNAL SPECTRUM

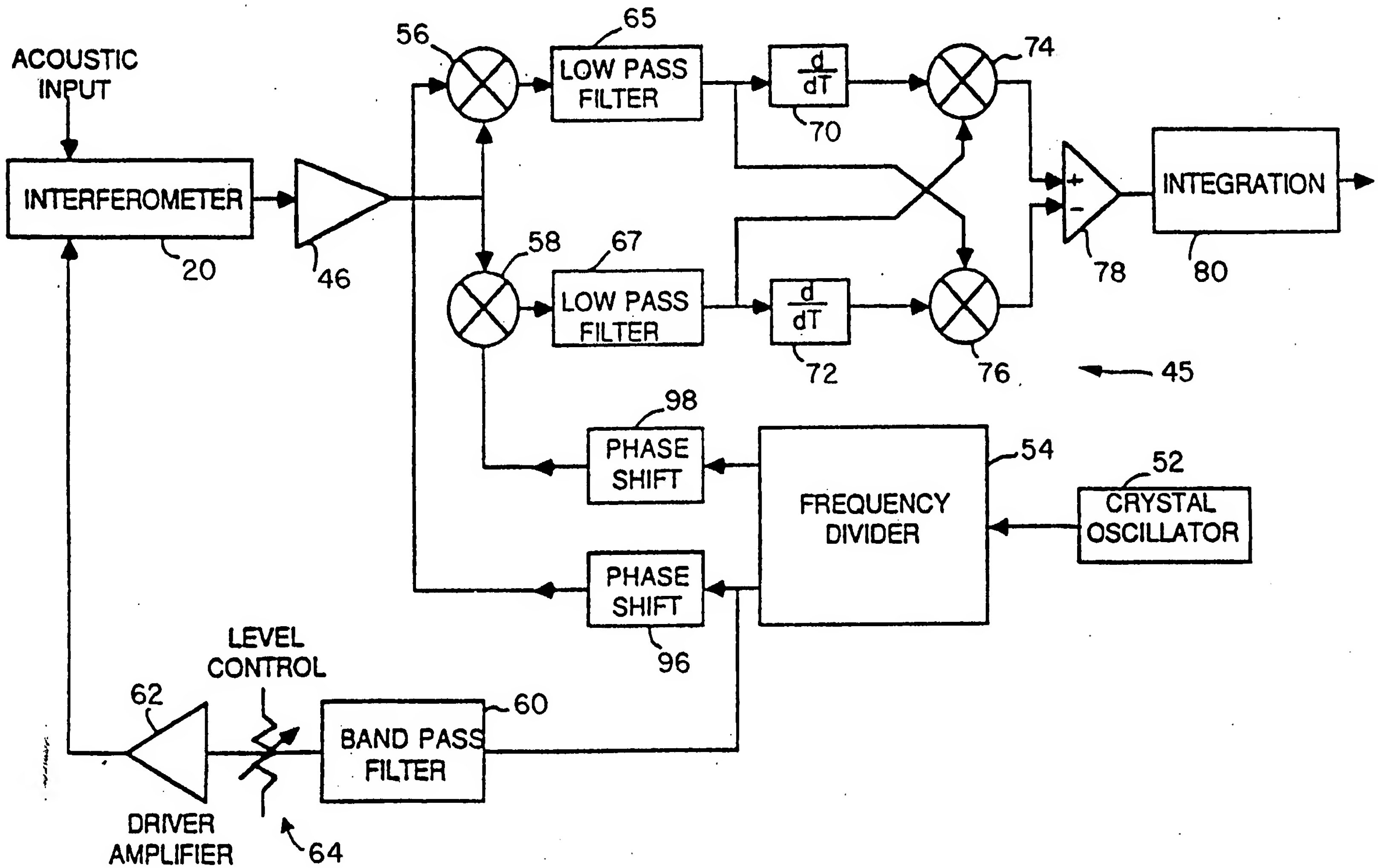

ACOUSTIC INPUT
INTERFEROMETER
20
46
56
58
65
LOW PASS FILTER
67
LOW PASS FILTER
d/dT
70
d/dT
72
74
76
+
-
78
INTEGRATION
80
45
98
PHASE SHIFT
PHASE SHIFT
96
FREQUENCY DIVIDER
54
52
CRYSTAL OSCILLATOR
LEVEL CONTROL
62
BAND PASS FILTER
60
DRIVER AMPLIFIER
64

FIG.6

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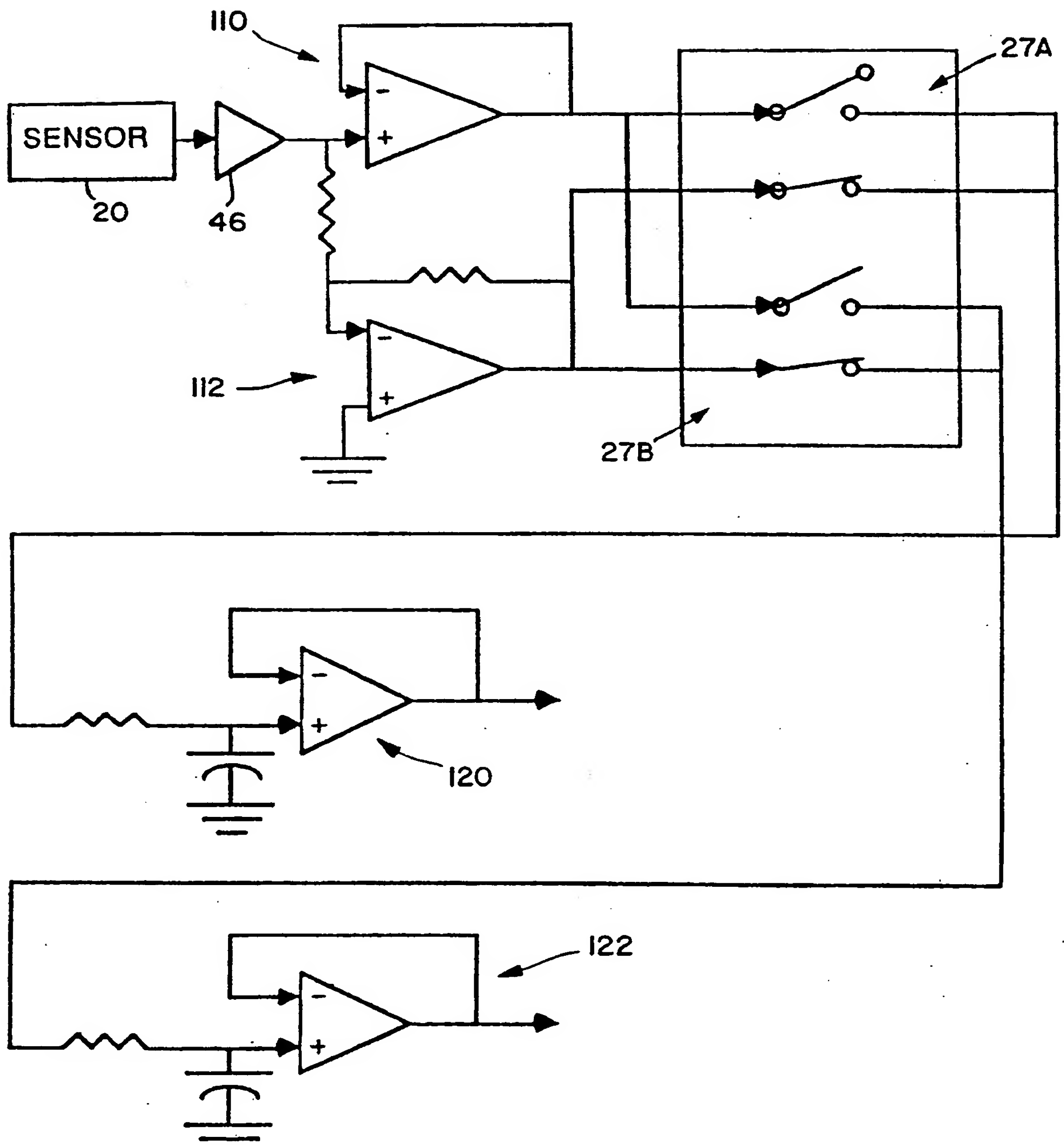


FIG.9

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# HYDROPHONE DEMODULATOR CIRCUIT AND METHOD

## BACKGROUND OF THE INVENTION

This invention relates to fiber optic interferometric sensors that respond to perturbations such as acoustic wavefronts by producing a phase difference in two light beams propagated by fiber optic material. Still more particularly, this invention relates to recovering the acoustic input signal from the signal developed by the optical fiber interferometer used to sense the acoustic energy.

Optical fibers can be made sensitive to a large number of physical phenomena, such as acoustic waves and temperature fluctuations. An optical fiber exposed to such phenomena changes the amplitude, phase or polarization of light guided by the fiber. Optical fibers have been considered for use as sensing elements in devices such as hydrophones, magnetometers, accelerometers and electric current sensors.

Mach-Zehnder, Michelson, Sagnac, and resonant ring interferometers have been used as sensors. Mach-Zehnder, Michelson and Sagnac interferometers respond to the phenomenon being sensed by producing phase differences in interfering light waves. Detecting phase changes in the waves permits quantitative measurements to be made on the physical quantity being monitored. The Sagnac interferometer produces phase differences in two counter- propagating light waves in a coil of a single fiber in response to rotations about the axis of the coil.

The Mach-Zehnder interferometer is particularly suited to sensing acoustic vibrations. A fiber optic Mach-Zehnder interferometer typically has a reference arm comprising a first length of optical fiber and a sensing

interferometer. The drift causes changes in the amplitude of the detected signal (signal fading), and distortion of the signal (frequency up-conversion).

Several detection schemes are currently available: passive homodyne, active homodyne (phase tracking), true heterodyne, and synthetic heterodyne. Each of these techniques has both advantages and disadvantages.

At this time, only the active homodyne has reached a level of high performance (10 to $10^{-6}$ rad sensitivity range with good linearity and low harmonic distortion), packageabilty (<24 $cm^3$), and low power consumption. In order to achieve this high level of performance, the technique requires relatively large piezoelectric phase modulators and fast reset circuitry. Large modulators are undesirable in multielement sensors since they increase the active sensor's size and decrease its reliability. Additionally, the need for the sensor circuitry to reset itself every time the environmental noise drives it past its dynamic range adds additional noise. A passive, rather than an active, homodyne system, obviates the two problems discussed above.

According to one aspect of the invention, there is provided a hydrophone demodulator circuit for demodulating an acoustic input signal, comprising:

means for generating a reference signal;

means for modifying an acoustic input signal into a form that can be demodulated;

means for mixing the reference signal with the modified input signal;

means for filtering the mixed signal; and

means for modifying the filtered signal into a demodulated output signal.

According to a second aspect of the invention there is provided a method for demodulating signals indicative of an acoustic input signal, incident upon a hyrophone, comprising the steps of:

A crystal oscillator frequency reference and passive filtering be used, which cause low phase noise. One may also include digital phase shifters for mixer references, which provide low phase noise and stable gain. The signal processing techniques of the circuit are applicable to sensor arrays using a single carrier excitation source, time demultiplexing of individual carrier signals and demodulation of each sensor carrier signal. This demodulator circuit is also applicable to frequency-multiplexed approaches, which utilize direct frequency modulation of the source, slightly unbalanced interferometers, and electronic frequency-division multiplexing.

The demodulation approach avoids signal fading in the interferometer in the time division multiplexed approach by length-modulating the reference fiber at a frequency above the input signal frequency range. Derivations have shown that the baseband input signal can be recovered by processing signals found in the frequency bands around the fundamental and the first harmonic of the reference fiber modulation frequency. In the frequency-multiplexed scheme, signal fading is avoided by frequency modulating the laser directly.

The hydrophone demodulation circuit may provide the reference fiber modulation drive (or corresponding laser frequency-modulation drive) and the interferometer output signal processing.

in a first channel, and a second mixing means for mixing the second desired reference frequency with the modified input signal in a second channel.

Additionally, there may be means for reducing the carrier ripple in the output of the first mixing means in the first channel, and means for reducing the carrier ripple in the output of the second mixing means in the second channel.

The circuit may also comprise means for differentiating the signal in the first channel, means for differentiating the signal in the second channel, means for multiplying the undifferentiated signal in the second channel by the differentiated signal in the first channel, means for multiplying the undifferentiated signal in the first channel by the differentiated signal in the second channel, means for taking the difference between the first multiplied signal and the second multiplied signal, and means for integrating the difference between the first multiplied signal and the second multiplied signal to form a demodulated output signal.

signal in the first channel, differentiating the signal in the second channel, multiplying the undifferentiated signal in the second channel by the differentiated signal in the first channel, multiplying the undifferentiated signal in the first channel by the differentiated signal in the second channel, taking the difference between the first multiplied signal and the second multiplied signal, and integrating the difference between the first multiplied signal and the second multiplied signal to form a demodulated output signal.

For a better understanding of the invention and to show how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawings, in which:

Figure 1 schematically illustrates a Mach-Zehnder interferometer;

Figures 2A and 2B graphically illustrate the demodulator input signal with the fundamental signal peaked;

Figures 3A and 3B graphically illustrate the demodulator input signal with the second harmonic peaked;

Figures 4A and 4B graphically illustrate the demodulator input signal with equal amplitudes for the fundamental and second harmonic;

Figure 5 graphically illustrates the peak-detected interferometer signal power spectrum;

Figure 6 schematically illustrates apparatus of the present invention for demodulating an acoustic input wave detected by a hydrophone;

Figure 7 schematically illustrates oscillator and mixer reference circuits that may be included in the apparatus of Figure 6;

Figure 8 schematically illustrates a P21 or laser current driver amplifier circuit that may be included in the apparatus of Figure 6;

different lengths; however, it is possible to form the interferometer 20 to have equal arm lengths. Light propagating in the reference arm 28 is called the reference signal, and light propagating in the sensing arm 30 is called the sensing signal. The coupler 23 couples a portion of the sensing signal back into the fiber 24 for output at port 23B while also coupling a portion of the reference signal into the sensing fiber 25 for output from the interferometric sensor 20 at port 23D. A portion of the reference signal continues to be guided by the fiber 24 and propagates from port 23A to port 23B. The coupler 23 combines portions of the reference and sensing signals and produces an output signal at port 23B that is a superposition of portions of the reference and sensing signals.

The result of combining the reference and sensing signals is the formation of an interference pattern between the reference and sensing signals at port 23B. This interference pattern is a function of the phase difference $\phi$ between the reference and sensing signals and is the output of the Mach-Zehnder interferometer 20 that is supplied to a detector 26.

The sensing arm 30 and the reference arm 28 may have quiescent lengths such that the sensing signal and the reference signal combine in phase in the coupler 23. The physical parameter, such as acoustic vibrations, to be measured is coupled to the sensor arm 30 by any convenient means, depending upon the parameter. Changes in the parameter while the reference arm 28 is isolated from changes in the parameter produce an optical path length change $\Delta L$ in the sensor arm 30, which causes a phase shift between the reference signal and the sensing signal. The Mach-Zehnder interferometer 20 may be calibrated so that

piezoelectric crystal 33 used to modulate the fiber length.

The detector 26 preferably includes a gated photodiode. The output of the detector 26 is the interferometer output signal. The phase modulation information in the frequency bands centered at 10.4 kHz and 20.8 kHz is used to recover the interferometer baseband input signal.

The character of the interferometer output signal is shown in Figures 2, 3 and 4. These figures illustrate the changes that occur in the signal and its spectral content as ambient pressure and temperature vary the relative lengths of the signal and reference arms of the interferometer. A 1 kHz, 50 mrad rms sinusoidal input signal was applied to the interferometer.

In Figure 2 the 10.4 kHz fundamental is peaked. The 1 kHz interferometer signal information appears as sidebands around the 20.8 kHz first harmonic. In Figure 3 the situation is reversed, so that the signal sidebands are referenced to 10.4 kHz while the 20.8 kHz harmonic is maximized. Figure 4 shows the signals for a condition intermediate to the other two interference lengths.

The reference fiber modulation drive provided by the demodulation circuit is adjusted to equalize the peak power in the 10.4 kHz and 20.8 kHz carriers. Figure 5 shows the input signal spectrum peak-detected over a long enough time such that all frequencies have peaked during the observation. The first two peaks on the left are the 10.4 kHz and 20.8 kHz carriers used by the demodulator circuit to recover the hydrophone signal.

For phase deviation much less than one radian, the power in each sideband relative to the carrier power can be shown to be

$$\mathrm{dBc} = 20 \log \phi_{rms} - 3. \tag{1}$$

fiber length is obtained.

The interferometer 20 produces output signals that contain information in the bands around 10.4 kHz and 20.8 kHz that can be used to recover the signal fiber baseband input signal. After buffering by a buffer circuit 46, the interferometer output signal is separated into a first and second channel. In the first channel the interferometer output signal is mixed with the 10.4 kHz reference signal by the mixer 56. In the second channel the interferometer output signal is mixed with the 20.8 kHz reference signal by the mixer 58. The output signal from the mixers 56 and 58 are low pass filtered through the low pass filter units 65 and 67, respectively. The filtering removes mixer products out of the signal bandwidth of interest.

The outputs of the low pass filter units 65 and 67 are each differentiated by a first and a second differentiator 70 and 72, respectfully. A pair of multiplying circuits 74 and 76 multiply the output of each channel from the differentiator 70 or 72 by the low pass filter output of the other channel. The resulting outputs of the multipliers 74 and 76 are then subtracted from one another by a difference amplifier 78. The outcome of the subtraction is then integrated by an integrator 80 to obtain the final output voltage that represents the length modulation of the signal fiber in the interferometer 20.

Referring to Figure 7, the oscillator and counter circuit provide the 10.4 kHz input to the PZT driver amplifier 62. The 10.4 kHz reference is phase-shifted by a digital phase shifter (shift register) circuit 96, and the phase shifted 10.4 kHz signal is input to the mixer 56. The 20.8 kHz

100 ohms and is short-circuit protected. The output drive circuit includes an operational amplifier 103 and a current driver 105 and associated components that are well known in the art.

Referring to Figure 9, the output of the interferometer 20 is input to the buffer 46. This input signal to the buffer 46 contains the 10.4 kHz and 20.8 kHz carriers and their respective sidebands. The input signal amplitude is typically about 2 Vpp. The buffer amplifier 46 provides gain adjustment from 1 V/V to 3 V/V. The input signal has nearly constant amplitude; however, its predominant frequency content shifts from 10.4 kHz to 20.8 kHz and back as interferometer ambient temperature and pressure varies.

The amplified input signal is buffered by a non-inverting unity gain amplifier 110 and an inverting unity gain amplifier 112. Two alternate action switches 114A and 114B provide the mixing function. The switches 114A and 114B are connected to the non-inverted and inverted signals so that full-wave mixing (synchronous demodulation) is obtained. The mixer switches 116 are driven by the 10 kHz REF and 20khZ REF obtained from the phase shifters 96 and 98. The mixer gain is $(2/\pi)$ $V/V_p$ in translating the carrier band signals to the baseband.

The mixers 56 and 58 translate the signals at their respective frequency to dc (the sidebands become baseband signals). Therefore, we will observe a slowly varying voltage in the filtered mixer output that varies with the corresponding carrier level. If the carrier reverses phase, the mixer output voltage reverses polarity.

The full wave mixer outputs are low-pass filtered (3.6 kHz at 3-dB) and buffered by buffer amplifiers 120 and 122 before being fed to the low pass filter sets 65 and 67. This is done to remove the mixer output

166. Subtracting one multiplier 164 or 166 output from the other in the difference amplifier 168 yields the derivative of the interferometer signal.

The final amplifier is an integrator 170 that integrates the output of the difference amplifier 168 for frequencies above about 5Hz. The input to the integrator 170 is preferably ac coupled ($3\mu F \times 39K\Omega = 0.117$ s) to reduce the very-low frequency signals generated by ambient temperature and pressure variations. The low frequency limit (about 5 Hz) for the integrator 170 may be set by a resistor (not shown) and a capacitor (not shown).

A symmetrical fiber optic directional coupler suitable for use in single mode fiber implementations of the invention is described in the March 29, 1230 issue of <u>Electronics Letters</u> Vol. 18, No. 18. pp. 260-261 and in U.S. Patent 4,493,528 issued January 15, 1985 to Shaw et al. That patent is assigned to the Board of Trustees of the Leland Stanford Junior University. The disclosure of that patent is incorporated by reference into the present disclosure. The fiber optic hydrophone structure described herein may be formed using other well-known types of optical couplers.

Other fiber optic couplers such as the tapered biconical coupler may also be used to couple light between optical fibers included in this invention

This invention is described with reference to a specific preferred embodiment. The invention is not limited to the structure or process steps described herein which exemplify the invention rather than limit it.

comprises;

means for removing the harmonic component from the first reference frequency;

means for controlling the output voltage of the means producing a reference fiber modulation frequency; and

means for driving the output voltage to the interference measuring means.

5. The hydrophone demodulator circuit of claim 3 or 4 when appended to claim 2 wherein the interference measuring means comprises:

a reference arm;

a sensing arm;

means for outputting a signal containing information in the frequency bands around and between the first reference frequency and the second reference frequency as the modified input signal;

means for buffering the modified input signal upon output from the interference measuring means; and

means for connecting the buffered modified input signal to the mixing means.

6. The hydrophone demodulator of any one of the preceding claims, wherein the mixing means comprises: means for separating the modified input signal into a first and a second channel;

a first mixing means for mixing a first reference frequency with the modified input signal in a first channel; and

a second mixing means for mixing a second reference frequency with the modified input signal in a second channel.

7. The hydrophone demodulator of claim 6, wherein the filtering means comprises:

means for reducing the carrier ripple in the output of the first mixing means in the first channel; and

frequency;

dividing the approximate 1 MHz signal into a second frequency;

shifting the phase of the first frequency;

shifting the phase of the second frequency; and

inputting the first frequency into the means modifying the acoustic input signal.

11. The method of claim 9 and 10, wherein the step of modifying the acoustic input signal comprises the steps of:

producing a reference fiber modulation frequency for the means modifying the acoustic input signal;

measuring the interference pattern of light propagating in two optical fibers; and

inputting an acoustic wave input to the interference measuring means.

12. The method of claim 10 and 11 wherein the step of acoustic input signal modifying comprises the steps of:

removing the harmonic component from the first reference frequency;

controlling the output voltage of the means producing a reference fiber modulation frequency; and

driving the output voltage to the interference measuring means.

13. The method of claim 11 or 12 when appended to claim 10, comprising the steps of:

providing a reference arm;

providing a sensing arm;

outputting a signal containing information in the frequency bands around and between the first reference frequency and the second reference frequency as the modified input signal;

buffering the modified input signal upon output from the interference measuring means; and

connecting the buffered modified input signal to

described with reference to Figures 6, or that figure as modified by Fig 7, 8, 9, 10 and/or 11 of the accompanying drawings.

18. A method of demodulating substantially as hereinbefore described with reference to Figs. 6, or that figure as modified by Figures 7, 8, 9, 10 and/or 11 of the accompanying drawings.

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